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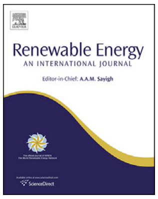

On the definition of the power coefficient of tidal current turbines and efficiency of tidal current turbine farms

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ABSTRACT

During the last decade, the development of tidal current industries has experienced a rapid growth. Many devices are being prototyped. For various purposes, investors, industries, government and academics are looking to identify the best device in terms of of cost of energy and performance. However, it is difficult to compare the cost of energy of new devices directly because of uncertainties in the operational and capital costs. It may however be possible to compare the power output of different devices by standardizing the definition of power coefficients. In this paper, we derive a formula to quantify the power coefficient of different devices. Specifically, this formula covers ducted devices, and it suggests that the duct shape should be considered. We also propose a procedure to quantify the efficiency of a tidal current turbine farm by using the power output of the farm where no hydrodynamic interaction exists between turbines, which normalizes a given farm's power output. We also show that the maximum efficiency of a farm can be obtained when the hydrodynamic interaction exists.

1. Introduction

Tidal energy has been utilized since Roman times, or before [1], when ancient people put their tidal mills in the water to harness energy by utilizing the elevation change of the tide. This resource is called tidal range and the technology used to harness the energy is called the tidal barrage. However, during the last few decades, this technology has not been used much to extract energy because of its low efficiency and high environmental impact. In late 1990s', the tidal energy gained the attentions again with a significant change of the energy conversion technology. The energy converter changed to underwater turbine which is analog to wind turbine, a successful technology to generate energy from air flow (Fig. 1), and this resource is called tidal current. A few companies have deployed their design in full-scale in the sea. Because these designs are approaching the commercial stage, several governments have begun to focus on identifying the most promising device for market acceleration. Technological investigations are being pursued to help facilitate commercialization and support industry growth [2,3]. Similarly, some private investors are also trying to identify the best device to evaluate potential investment opportunity [4]. Additionally, researchers are optimizing the devices to reach the cost-effectiveness from an engineering point of view [5,6].

To determine whether a turbine is worth investigating, the project developer usually uses the cost of energy to check the cost-effectiveness of a turbine or turbine farm. The cost of energy is defined as the ratio of the total cost to the total energy output over the lifetime of a turbine or farm. Mathematically, it can be estimated by using Eq. (1).

$$c_{\mathrm{energy}} = \frac{\sum_j \mathrm{levco}_j}{\sum_j \mathrm{Energy}_j} \tag{1}$$

where levco_j and Energy_j denote the levelized cost (present value of the total cost of building and operating a power plant over its economic lifetime) and the energy output in the year j, respectively. The levelized cost is directly determined by the turbine materials and operational strategies [7]. Because the tidal current industry is still developing new turbine materials as well as operational strategies, it is difficult to evaluate the cost of energy. Thus, it can be more productive to study the total energy output, which is expressed as follows,

$$\mathrm{Energy} = \mathbb{E}(P(t), f, T) \tag{2}$$

where $\mathbb{E}$ denotes the function of calculating the total energy output, P denotes the power output, t denotes instant time, f denotes the electric conversion efficiency, and T denotes the lifetime of the device or farm.

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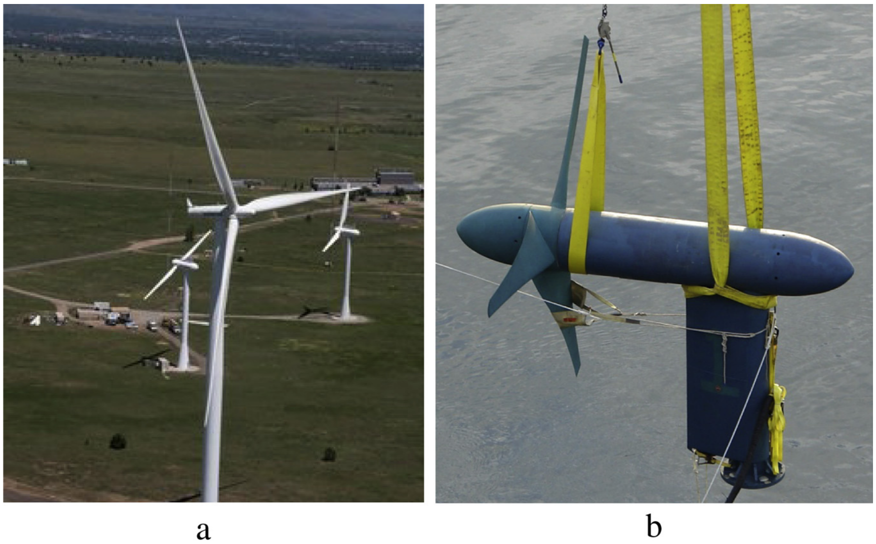

Fig. 1. Examples of turbines: (a) wind turbine (at NREL) and (b) tidal current turbine (courtesy by Verdant power).

As the energy output is highly site dependent, researchers always turn to focus on the power output. In order to standardize this discussion, researchers quantify the power output of the turbine by analyzing its dimensionless format, power coefficient. However, there is currently no universally accepted definition of power coefficient for tidal current turbines because dozens of new prototypes with nontraditional designs have emerged during the past decade. The traditional definition does not consider the auxiliary structures such as duct and flapping foil. Consequently, it is difficult to use the traditional definition to evaluate the cost-effectiveness of a nontraditional turbine system. In order to provide a precise method to quantify the power output of different designs, we propose a new way to calculate the power coefficient that applies to both traditional and nontraditional turbines, and we summarize the effort in this paper. Specifically, after reviewing the traditional turbine design, we discuss the difference between the design of the nontraditional turbines and the design of traditional turbines. Then, we propose a new reference power to calculate power coefficient that handles both the nontraditional turbines and traditional turbines. Examples of nontraditional turbines are shown, as well as a procedure to quantify the farm efficiency for the purpose of resource assessment and farm planning. To obtain the farm efficiency, we suggest that one shall use the power output of the farm where no hydrodynamic interaction exist between turbines as the reference power to normalize a farm power output. Finally, we discuss the limitations of the new methods.

2. Definition of turbine power coefficient

The turbine power coefficient is defined as the actual power output divided by a certain reference power output. For the simplicity of future discussion, we define a parameter, P_{ref}, as the reference power which is used to nondimensionalize the actual power output; consequently, the power coefficient of a generic turbine can be given as Eq. (3). This reference power output is determined by the geometry of the turbine and the characteristics of the inflow.

$$C_P = \frac{P}{P_{\text{ref}}} \tag{3}$$

2.1. Traditional turbine

For traditional turbines, i.e., open water vertical-axis turbines and horizontal-axis turbines (Fig. 2), the power output is nondimensionalized by the maximum power output that can be generated from the kinetic energy flux of a free stream flow through the turbine projected frontal area, the velocity of which is uniform in space and constant in time. Theoretically, for such an undisturbed free stream flow through $1/2\rho AU_\infty^2$ (where ρ, A and U_∞ denote the water density, the frontal area of the turbine and the far-field incoming flow velocity, respectively), we can have the maximum power output as $1/2\rho AU_\infty^3$. Therefore, to evaluate the power coefficient of a traditional turbine, the reference power for the traditional turbine can be given as,

$$P_{\text{ref,trad}} = \frac{1}{2}\rho AU_\infty^3 \tag{4}$$

Thus, we have what we often see in textbooks and articles about the turbine power coefficient,

$$C_P = \frac{P}{\frac{1}{2}\rho AU_\infty^3} \tag{5}$$

2.2. Nontraditional

Recently, quite a few nontraditional designs have been proposed and built, among which ducted turbines most popular.[1] Some have been developed by companies such as Lunar Energy, Clean Current and Open Hydro and some are developed by universities such as the University of Buenos Aires [8], and the University of British Columbia [9]. The main purpose of using the duct is to augment the flow passing through the turbine so as to increase the power output. The more optimal the duct profile is, the higher the turbine power output is. Therefore, it is not always suitable to use the traditional power coefficient definition, Eq. (5) to dimensionalize the power output because of the definition of the frontal area, A, and the incoming flow velocity U_∞. Some suggest that the frontal area shall be kept as the original front area [11], i.e.,

$$A = \pi r^2 \tag{6}$$

where r denotes the turbine radius in the duct. Some suggest that the frontal area shall be the frontal area of the duct [12], i.e.,

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[1] Here, duct refers to the shroud structure around the turbine (see Fig. 3). Those large structure around turbine such as dam or barrage type are not considered here. They are beyond the scope of this paper and won't be discussed.